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ADAPTIVE AND SELF-OPTIMIZING CONTROL

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By

Rufus Oldenburger

Principal Investigator

School of Mechanical Engineering

Purdue University

Contractor:

Purdue Research Foundation
Lafayette, Indiana

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This report covers the period of February 1, 1962 to February 1, 1963. A large part of the effort during this year was devoted to completing the research of L. J. Schrock and the writer on "Quenching of adaptive control system response to test signal" and preparing the results for publication. A technical report with the above title was issued in March, 1962 to the Distribution List, and a paper with the same title was presented to the American Institute of Electrical Engineers at the AIEE Fall General Meeting, Chicago, Illinois, October 11, 1962. This paper (AIEE No. 62-1382) will be published in the AIEE Transactions. The problem of quenching arose in a study of adaptive control. The theory actually applies to quenching the response of a system to a known signal whether or not adaptive control is involved. A test signal may be employed to identify the parameters of a system to be controlled. In adaptive control this identification is done automatically.

Unfortunately, the test signal disturbs the system, resulting in an undesired response. This response may be of appreciable magnitude and duration. As soon as the system is known, the response of the system to an arbitrary input can be computed. The problem is to quench the response to the test signal by the introduction of an appropriate signal. The systems treated are assumed to be described by linear differential equations with slowly varying coefficients so that these coefficients may be assumed to be constant during a given identification, and subsequent quenching, period. Two cases are treated. One occurs where the input is unbounded. In this case the quenching signal is a linear combination of a properly weighted impulse and weighted derivatives of this impulse. Such combinations may be approximated in practice. Quenching is assumed to be optimum if the integral squared error is a minimum.

In the second case the absolute value of the input is bounded. In this case quenching that is optimum in every reasonable engineering sense can be obtained. The bounded quenching signal is obtained by scheduling the lengths of time that its value is either at the upper or lower bound. As soon as the system is identified, quenching can be accomplished by scheduling of the system input, regardless of the other disturbances to which the system is subject during identification and quenching. If the system to be identified is simple second order, that is, a double integrator with gain as a parameter, and the test signal is a step input, the quenching signal is independent of the system and depends only on the test signal and the known bound on the input. Thus it is relatively easy to schedule the quenching signal in this case. If the system to be identified also involves a first order lag, the quenching signal, up to the instant it is removed, is independent of the system parameters. The instant of removal depends on the time constant of the system, but not the system gain. Thus it is again relatively easy to schedule the quenching signal. This signal is computed without a knowledge of system characteristics until the system time constant is determined. When this time constant is known, the shut off time is computed. Thus in the basic cases treated, the quenching signal is independent of system gain. The physical equipment required for quenching is simplified accordingly.

When a controlled system has been identified, a mathematical model of it can be constructed. In automatically adapting the controller to the system, the characteristics of the controller are made to match those of the system model. In using the model it is assumed that the responses of the model and the system to the same input are identical for practical purposes. Actually they differ, and the designer should know by how much. The delay line synthesizer has been employed successfully for identification. The synthesizer is based on the principle that a rational transfer derivative operator may be represented by an infinite series, where this series is a linear combination of pure delays, all of these delays being positive integral multiples of a given delay. In physical applications it is possible to work only with a finite number of terms. The closeness with which the response of the delay line model agrees with that of the system depends on the number of terms of the infinite series kept for the model, and on the nature of the input. Research on this subject began with first order systems. Substantial mathematical simplification of the problem was achieved by writing the transfer operator as an infinite product of linear operators. The principle investigator had previously used the same technique to simplify the mathematics of systems with distributed constants. By this technique it is possible to write the transfer operator of the model as a product of the transfer operator of the given system by an operator that can be readily approximated to any desired accuracy. The effect of the second factor on performance can be conveniently determined. The responses of the model and system to commonly occurring inputs such as steps, sinusoids, pulses and ramps were correlated with the number of terms used in the model. These results are being extended to other inputs and higher order systems. Experience shows that the transfer characteristics of physical systems to be controlled generally can be represented by rational operators to sufficient accuracy for engineering design purposes.

In practice, the inputs or rates of change of inputs to a controlled system are physically bounded or limited by the designer to protect the equipment. The problem of nonlinear control is that of obtaining the best control subject to the bounds involved. Since in this case the controller is generally nonlinear, such control is said to be optimum nonlinear. The bounds are often on the absolute values of the rates of change of the inputs. The principal investigator treated linear systems with one controlled variable and one controlling variable with the rate of change of the controlling variable bounded. He proved that under rather general conditions a single control function will yield optimum response to step disturbances. This function will not give optimum or near optimum response to arbitrary disturbances since staircase approximations to commonly occurring random disturbances involve intervals between steps that are too short. The situation is different if piecewise linear approximations are employed where the slopes of the line segments are arbitrary. A disturbance is said to be controllable if its rate of change is such that a perfect controller can keep up with the disturbance and maintain the system error at or very near zero. If the rate of change is too great this is not possible, a system error will arise, and the disturbance is uncontrollable. Successful controllers are designed so that the disturbances are largely controllable.

Otherwise there would be continually objectionable system errors and the controller would be relatively ineffective. In engineering practice enough power usually is selected for the controller so that the disturbances are controllable. One would then expect disturbances fluctuating violently or rapidly from one direction to the other to be infrequent. This is actually the case so that a disturbance may be approximated by a piecewise linear one where near optimum control can be obtained by using a control function chosen to give optimum response to a ramp disturbance. N. P. Smith and the principal investigator obtained this function for commonly occurring linear systems. When control with this function was tested on an analog computer it was found that definitely better response was obtained for arbitrary as well as ramp disturbances than can be secured by known techniques, such as with a control function optimum for step disturbances. This discovery led to an analytical study of the reasons for the unexpected improvement obtained in the laboratory.

The principal investigator proved that if an uncontrollable disturbance is followed by a sufficiently long controllable portion, and the disturbance is known in advance, there is one and only one best action of the controller that will yield a response optimum in every reasonable engineering sense, such as minimum time to equilibrium where the system error is zero, minimum area between the error curve and the time axis, minimum overswing, minimum underswing, etc. A controller is said to be near optimum if it yields approximately the same system response as if the disturbance were known in advance. It was proved that the control function optimum for ramps normally yields nearly optimum response to an uncontrollable disturbance followed by a one or two segment piecewise linear controllable section. An effort is being made to extend the proof to an uncontrolled disturbance followed by a piecewise linear controllable section composed of an arbitrary number of straight line segments. The controller optimum for ramps essentially adapts itself to the rate of change of the disturbance. Until now optimum control studies have been limited almost entirely to bringing a system from one state to another while the system is undisturbed during the transition. The new approach allows the system to be subject to an arbitrary disturbance while the controller brings it from its initial to its final state.

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